ANTENNA DIAGNOSTICS OF THE DUST IN SPACE PLASMAS

M. V. Shatalina* and E. A. Mareev*

Abstract

The principles of antenna diagnostics of dusty plasma are discussed. On the basis of reciprocity relation the electric potential, induced by the grains passing by the long dipole antenna, is calculated. Along with the monopole component, a possible presence of an oscillating dipole moment due to the grain shielding is taken into account. In the case of a dust flow the spectrum of the electric field fluctuation, induced on the antenna, is calculated as a result of the averaging on the ensemble of dust particles moving near the receiving antenna. The applicability of the method developed is noted for the spectroscopy of aeroelectric structures in aerosol plasmas.

1 Introduction

Dust is widely spread in space, including Solar wind plasma, tails of the comets, planetary rings and planetary atmospheres. Sometimes the presence of the dust can essentially influence the characteristics of ambient plasma [Goertz, 1989; Tsytovich, 1997]. As a rule, dust particles acquire a charge which is much more than an electron charge. Much of the characteristics of the dust in space are still poorly studied. Nowadays both remote and in–situ methods of space plasma diagnostics are used to obtain information on the dust particles in space plasma. In this paper we focus on the use of a satellite–borne antenna to examine some dust characteristics from the antenna response on dust particle flybys. In particular, the radio dust analyzer (RDA) method has been suggested by Meuris et al. [1996]. This method uses a wire dipole antenna imbedded in space plasma; charged dust grains passing by the antenna induce an electric potential charge during the flyby time. These "waveforms" can be studied as a function of the characteristics of the dust grain (its charge and velocity vector) and the plasma parameters.

We can generalize also this method applying it for the study of aerosol plasmas. Namely, we have considered the contribution of aeroelectric structures, induced an electric field perturbation when measuring electric field noises in the atmosphere, and its contribution can be calculated by the probe particle method [Rostoker and Rosenbluth, 1960].

*Institute of Applied Physics, Russian Academy of Sciences, Ulyanova str, 46, 603950, Nizhny Novgorod, Russia. *In the time between the PRE V conference and the edition of this proceedings issue M. V. Tolkacheva has married and her name is now M. V. Shatalina. Congratulations!*

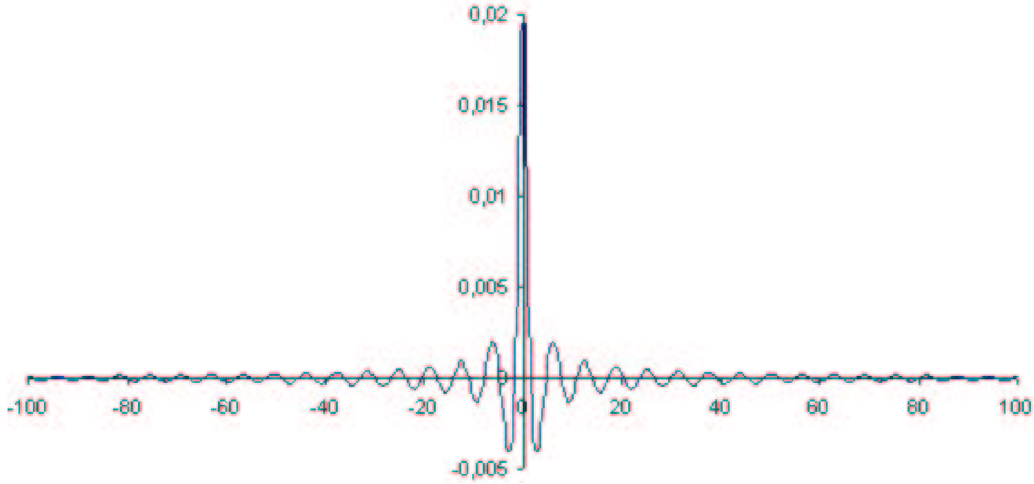

Figure 1: The voltage on a wire dipole antenna produced by a single grain.

2 Electric noise produced by a single dust grain

If the dust density in space is small we cannot consider the dust as a plasma component. But in a case of a rather large charge of the dust grain it can influence the antenna embedded in the plasma. In the case of a dust flow the spectrum of the electric field fluctuation, induced on the antenna, is calculated as a result of the averaging on the ensemble of dust particles moving near the receiving antenna. Let us examine the electrical signal produced by a single dust grain flying near the antenna. The reciprocity relation can be used in its electrostatic form:

$$\int_V \rho_1 \varphi_2 dV = \int_V \rho_2 \varphi_1 dV, \tag{1}$$

where $\rho_{1,2}$ is the charge density and $\varphi_{1,2}$ are the respective potentials.

Here ρ_1 is the density of dust grain charge, which is formed due to the monopole charge q and the oscillatory dipole moment P, ρ_2 is the probe charge density on the antenna. For a wire dipole antenna, oriented along the X–axis the dust grain flying along the antenna axis induces the following voltage:

$$\Delta\varphi_{mon} = \frac{2q}{L} \ln \left| \frac{L-(x-Vt)+\sqrt{(L-(x-Vt))^2+d^2}}{-(x-Vt)+\sqrt{((x-Vt))^2+d^2}} \right|, \tag{2}$$

$$\Delta\varphi_{dip} = \frac{2P_x e^{i\omega t}}{L} \left(\frac{x-Vt-\text{sign(x-Vt)}\cdot\sqrt{(L-(x-Vt))^2+d^2}}{(\text{sign(x-Vt)}\cdot(L-(x-Vt))+\sqrt{(L-(x-Vt))^2+d^2})} \times \right.$$

$$\left. \frac{1}{\sqrt{(L-(x-Vt))^2+d^2}} + \frac{1}{\sqrt{(x-Vt)^2+d^2}} \right), \tag{3}$$

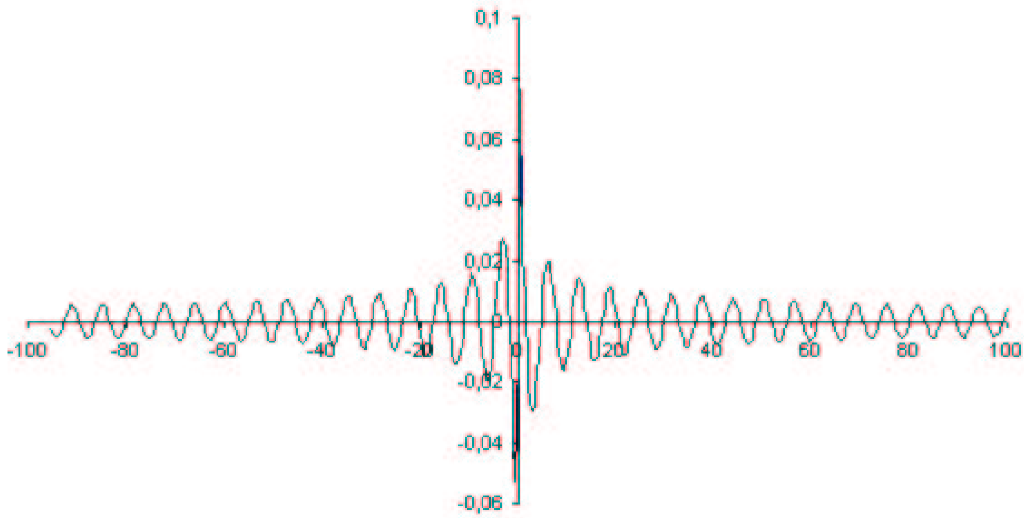

Figure 2: The voltage on a double–sphere antenna produced by a single grain.

where L is the antenna half–length, P_x is the projection of the dipole moment of a dust grain on the X–axis, d is the distance between antenna and dust grain, ω is the frequency of oscillations of the dipole moment of a dust grain.

For electric field measurements in space plasmas the double–sphere antennas are also widely used. For a double–sphere antenna oriented along the X–axis we can obtain:

$$\Delta\varphi_{mon} = q\left(\frac{1}{\sqrt{(L-(x-Vt))^2+d^2}} - \frac{1}{\sqrt{(L+(x-Vt))^2+d^2}}\right) \tag{4}$$

$$\Delta\varphi_{dip} = P_x e^{i\omega t}\frac{(x-Vt)}{((L-(x-Vt))^2+d^2)^{3/2}} \tag{5}$$

We built the plotted function of the summa of the voltages of monopole and dipole components (2) - (3) on Figure 1, and (4) - (5) on Figure 2 with $L = 25$ m, $V = 400$ m/s, $d = 3$ m. These functions can be compared to the signal on the wire dipole antenna which are sometimes recorded when measuring the potential on the antenna with high resolution depending on time [Mangeney et al., 1999]. P. Meuris (private communication) suggested that those signal can be induced by the high–charged particles flying over the dipole antenna, therefore one can use those results to obtain an information on the dust grains. We note that there is a peak in the signal spectrum close to the ion frequency of surrounding plasma.

3 Diagnostics of a dust flow in the aerosol plasma

To develop a method of dust spectroscopy in space plasma, we can generalize the above calculation for the case of a dust flow, averaging on the ensemble of dust particles moving near the receiving antenna. We start from the analysis of the signal induced at the observation point by the charge density perturbation possessed by a monopole charge q and a horizontal dipole momentum P_x.

The vertical electric field (E_z) of a single dust structure situated in $\vec{r'_0}$ at t_0 is given by

$$E_z(0,\vec{r'_0},t_0) = \frac{2qz'}{((x'-Vt)^2+y'^2+z'^2)^{3/2}} \tag{6}$$

for the monopole and

$$\frac{6P_x z'(x'-Vt)}{((x'-Vt)^2+y'^2+z'^2)^{5/2}} \tag{7}$$

for the horizontal dipole. Using the Fourier transformation we have:

$$E_z(0,\vec{r'_0},t_0) = \int_{-\infty}^{\infty} \exp(-i\omega_1 t) E_z(0,\vec{r'},\omega_1)d\omega_1 \tag{8}$$

$$E_z^*(0,\vec{r'_0},t_0-\tau) = \int_{-\infty}^{\infty} \exp(-i\omega_2(t-\tau)) E_z^*(0,\vec{r'},\omega_2)d\omega_2 \tag{9}$$

Then we average on the coordinates of probe structures to obtain the auto correlation function of the vertical component of the electric field:

$$\Psi_E(\omega) = \langle E_z(0,\vec{r'_0},t_0)E_z^*(0,\vec{r'_0},t_0-\tau)\rangle$$

$$= \int_{-\infty}^{\infty} \exp(-it(\omega_1-\omega_2)-i\omega_2\tau)\int_{V_{str}} \frac{N_t}{V} E_z(0,\vec{r'},\omega_1)E_z^*(0,\vec{r'},\omega_2)d\omega_1 d\omega_2 d\vec{r'} \tag{10}$$

where V_{str} is the volume of the probe structures. Let the number of structures N does not depend on the coordinates. The spectrum of one structure is given by

$$E_z(0,\vec{r'_\perp},\omega) = \frac{2qz'\omega\exp(i\omega x'/V)}{\pi V^2\sqrt{(y'^2+z'^2)}} K_1\left(\frac{\omega}{V}\sqrt{(y'^2+z'^2)}\right) \tag{11}$$

where $r' = (x',y',z')$ are the coordinates, q is the charge, V is the velocity of a single structure, and K_1 is the McDonald function. For the ensemble of structures we have:

$$\Psi_E(\omega) = \frac{8q^2\omega^2}{\pi}\int\int \frac{N}{V^3}\frac{z^2}{y^2+z^2}\int_{-\infty}^{\infty}\exp(-it(\omega_1-\omega_2)-i\omega_2\tau)\times$$

$$\int_{V_{str}} \frac{N}{V} E_z(0, \vec{r'}, \omega_1) E_z^*(0, \vec{r'}\omega_2) d\omega_1 d\omega_2 d\vec{r'} K_1 \left(\frac{\omega}{V} \sqrt{(y'^2 + z'^2)} \right) dydz \tag{12}$$

Let N =const. and all structures should have the velocity V and the height Z_0, then for $\omega >> V/Z_0$ we have an exponential spectrum:

$$\Psi_E(\omega) \propto \exp \left(-\frac{2\omega Z_0}{V} \right) \tag{13}$$

and for $\omega << V/Z_0$ the spectrum becomes constant:

$$\Psi_E(\omega) = -\frac{4q^2 N}{V Z_0} \tag{14}$$

For the dipole structure we can receive:

$$E_z(\omega, y', z') = \frac{12 P_x z' \omega \exp(i\omega x'/V)}{\pi V} \frac{\partial}{\partial u} \frac{u^2 K_2 \left(u \sqrt{(y'^2 + z'^2)} \right)}{3(y'^2 + z'^2)}, \tag{15}$$

where $u = \omega/V$. For $u << 1$ we have:

$$\Psi_E(\omega) = 2\pi V N \frac{16 P_x^2}{\pi^2 V^2} \frac{\omega^2}{V^2} \int_{-\infty}^{\infty} \int_0^{\infty} \frac{z^2 dydz}{(y^2 + z^2)^2} K_1 \left(\frac{\omega}{V} \sqrt{(y'^2 + z'^2)} \right) dydz \tag{16}$$

In particular, for the dipole structures in one plane ($r' = (x', y', z0)$):

$$\Psi_E(\omega) = \frac{16 P_x^2 N_s \omega^2}{z_0 V^3} \tag{17}$$

Formulas (13) - (17) are describing the behaviour of the low–frequency part of the spectra.

We can also generalize this method applying it for the study of aerosol plasmas. Namely, we can consider the contribution of aeroelectric structures, inducing an electric field perturbation when measuring electric field noises in the atmosphere, and its contribution to the spectrum of measured electric field fluctuations.

4 Conclusion

The method of antenna noise spectroscopy and its applicability for dusty plasma experiments were analyzed. The asymptotic results describe the behavior of the low–frequency part of the fluctuation spectra. This method of dusty plasma diagnostic seems to be interesting in space experiments applications.

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